OmniVib: Towards Cross-body Spatiotemporal Vibrotactile Notifications for Mobile Phones

Jessalyn Alvina[1,2] **Simon T. Perrault**[1] **Thijs Roumen**[1]
Shengdong Zhao[1] **Maryam Azh**[1] **Morten Fjeld**[3]
[1]NUS-HCI Lab, National University of Singapore
[2]INRIA, Univ Paris-Sud, CNRS (LRI), Orsay, France
[3]t2i Interaction Lab, Chalmers University, Sweden
alvina@lri.fr, perrault.simon@gmail.com, thijs.roumen@hpi.de, zhaosd@comp.nus.edu.sg, maryam@nus.edu.sg, fjeld@chalmers.se

ABSTRACT
Previous research has shown that one's palm can reliably recognize 10 or more spatiotemporal vibrotactile patterns. However, recognition of the same patterns on other body parts is unknown. In this paper, we investigate how users perceive spatiotemporal vibrotactile patterns on the arm, palm, thigh, and waist. Results of the first two experiments indicate that precise recognition of either position or orientation is difficult across multiple body parts. Nonetheless, users were able to distinguish whether two vibration pulses were from the same location when played in quick succession. Based on this finding, we designed eight spatiotemporal vibrotactile patterns and evaluated them in two additional experiments. The results demonstrate that these patterns can be reliably recognized (>80%) across the four tested body parts, both in the lab and in a more realistic context.

Author Keywords
Tactile feedback; mobile device; spatiotemporal vibrotactile pattern; notification; arm; palm; thigh; waist.

ACM Classification Keywords
H5.2 [Information interfaces and presentation]: User Interfaces – Haptic I/O.

INTRODUCTION

Vibration notification is a common, essential feature for mobile phones today [21]. This type of notification allows users to be alerted in a private, eyes-free manner, minimizing disturbance to people nearby.

Vibration notifications on contemporary mobile phones are mostly generated by varying temporal properties of a single motor, limiting its expressiveness. Researchers have investigated spatiotemporal vibrotactile patterns that are generated using multiple vibration motors arranged in different spatial locations played in sequence (Figure 1a) [16, 22, 23]. By distributing information spatially, these patterns not only provide additional design choices for practical use but also convey richer information (e.g., direction) that is not easily available with only temporal variations [7]. However, this benefit can be jeopardized depending on which body part the notification is received. Haptic sensation is significantly different across the body [10], and the perceived spatial organization of vibration pattern differs depending on the applied body part [2,12].

Furthermore, users tend to attach their phones at different body parts in varying contexts, with the common locations being the hand, trouser pocket, belt (next to waist), and arm (e.g., when exercising) [20]. A good notification design implies that the pattern can reliably recognized across these common body parts.

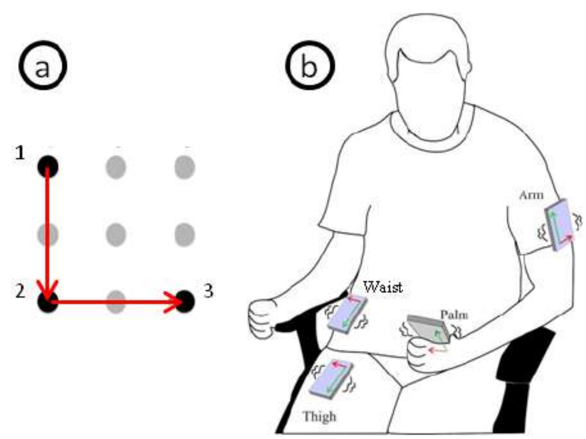

Figure 1: (a) Spatiotemporal vibrotactile shaped like an "L"; (b) OmniVib consists of a set of spatiotemporal vibrotactile patterns that can be recognized on four different body parts: *palm*, *arm*, *thigh* and *waist*. Red and green arrows show stimulus orientation relative to body parts.

While previous research, including *SemFeel* [24] and *T-mobile* [21], have shown promising potential for spatiotemporal vibrotactile patterns, the investigated patterns were tested only on the participants' palms. It remains to be seen if those patterns can be recognized across multiple body parts.

CHI 2015, April 18 - 23 2015, Seoul, Republic of Korea
Copyright is held by the owner/author(s). Publication rights licensed to ACM.
ACM 978-1-4503-3145-6/15/04…$15.00
http://dx.doi.org/10.1145/2702123.2702341

In this paper, we investigate the issue of cross-body recognizability of spatiotemporal vibrotactile patterns generated on a device platform the size of a mobile phone.

Our initial two studies investigated if patterns previously tested on the palm could be recognized at other body parts. To do so, we first studied if users could identify the absolute location of a single vibration motor as well as recognize the direction of two sequentially-located vibration motors across body parts. Our results showed that reliable recognition of either absolute location or direction of sequential vibration pulses within the size of a mobile phone is difficult, especially for the waist and thigh, with average recognition rates as low as 55% (except for the palm).

However, we discovered that users can still reliably distinguish whether or not a vibration pulse is played at the same location in quick succession. Based on these findings, we designed OmniVib, a set of eight cross-body spatiotemporal vibrotactile patterns. We then validated them in two additional studies. The first additional study found that users can reliably recognize these patterns with 86.3% accuracy (min 80%) across the four body parts. We then investigated the external validity of the previous finding by asking users to recognize these patterns while engaging in a primary visual task. Results showed that participants can achieve 87.5% accuracy for real world notification tasks under minimal training.

The three-fold contributions of this paper are the development of:

1) A series of studies to understand how users perceive single vibrations and strokes on different body parts. We found that users cannot reliably localize single vibrations and strokes on body parts except on the palm.
2) A set of spatiotemporal vibrotactile patterns that can achieve 80% to 92% recognition accuracy across common body parts. The effectiveness of these patterns for practical use was tested in an environment mimicking realistic settings.
3) A set of design guidelines to understand the constraints and possible extensions of our set of patterns.

RELATED WORK

Our review includes prior studies on vibrotactile patterns which focus on vibration-based notification interface on mobile devices.

Vibrotactile Pattern in Mobile Devices

Vibrotactile patterns can be divided into engineering, temporal, and spatial patterns. Engineering features contribute to pattern design mainly by manipulating the intensity (amplitude) or the frequency of the vibration [1, 3, 11]. Temporal patterns are composed of a sequence of vibrations generated on the same vibration motor and can be characterized by the duration of each vibration as well as the duration of the gap between two vibrations. In this work, we fixed the temporal parameters of our spatiotemporal vibrotactile pattern following suggestions from Saket et al. [17]: 600 ms for a vibration and 200 ms for gaps. As well, we treated engineering parameter as a controlled variable in which we set the vibrational intensity to be constant across all experiments as in [15, 24].

In addition to manipulating temporal or engineering parameters, another design approach is to use additional vibration motors to produce spatial patterns. Yatani et al. [22] used a 3×3 array of vibration motors to deliver spatial information via spatial patterns by mapping the *location* of the vibration motors to an 8-cardinal direction and amplitude to distance. In their other work [23], the spatial vibrotactile patterns were used to accompany visual feedback in spatial coordination tasks and demonstrated that vibrotactile feedback can reduce information workload in visual channel.

When spatial patterns are combined with temporal presentation, one can create *spatiotemporal patterns* by sequentially activating a number of vibration motors to “draw” lines or geometric shapes [1]. In 2008, Sahami et al. [16] explored the potential of using spatiotemporal patterns by embedding six vibration motors on the edge of a mobile device, three on each side. Three spatiotemporal vibrotactile patterns were tested: circular, top-down, right-left. Although no further investigation was done, the result showed that pattern recognition rate was more than 51%. In similar works such as Rantala et al. [15] and in *SemFeel* [24], good overall recognition rates (90% or more) have been observed; however, these works only considered the palm of the hand for location.

Tactile Perception across Human Body Parts

People often place mobile devices on different locations on their body. A survey revealed that the main reason people place their phones where they do is to have easy access to receive notifications [20]. Hence, they tend to put their mobile devices on their body: arm (e.g., arm band) palm (e.g., holding the phone), chest (e.g., shirt or jacket pocket), waist (e.g., waist belt), and thigh (e.g., trouser pocket). Karuei et al. [10] conducted a study to examine which body parts were more sensitive in detecting a single vibration and found that the thigh and feet are the least sensitive body parts, followed by waist, arm, and chest. Wrist proved to be the most sensitive; back, thigh, and abdomen also share a similar sensitivity towards vibrotactile stimuli [5].

The wrist’s sensitivity was confirmed in *BuzzWear* [11], where users could recognize 24 patterns with a good accuracy after 40 minutes of training. Pasquero et al. [14] also investigated whether people could count the number of vibrations generated on their wrist and determined that, depending on the length of each vibration, participants could easily count up to 10 vibrations. While this indicates a good potential for tactile feedback for wristwatches, taking advantage of the sensitivity of the wrist for a mobile-phone-sized device proves difficult. Other works investigated other body parts, such as forearm [9] or cheek [13], which are out of the scope of our investigation.

Notably, there are many factors that may affect recognizability of vibrotactile patterns when placed on different body parts, since all parts have different levels of sensitivity and spatial acuity [1]. Fingertip [2] has the highest vibrotactile sensitivity and spatial acuity, followed by palm and then thigh. There is more sensitivity for arm areas around the joints (i.e., wrist, elbow and shoulder) than the center of arm [3]. On abdomen area, the navel is more sensitive as compared to the areas around them [4]. The orientation of a pattern becomes an important factor since perceived spatial organization of vibrotactile patterns differs depending on the body part [12].

Gap between Two Vibration Motors

The difference in recognition sensitivity can be illustrated by the minimum gap distance between vibration motors required for one to notice. To determine the minimum gap distance, Gibson & Craig [6] used two contactors to form spatial patterns with a variety of gap distances and conducted a study where users had to determine whether or not a spatial pattern was within a gap. They estimated the minimum gap distance for fingertip, finger base, palm, and forearm. The expected ratio is 1:1.5:2.9:4.2, respectively (thus, the ratio of palm to forearm is 1:1.45). The general trend illustrates that the less sensitive the body part is, the larger the distance required for distinguishing two separate points. *Orientation* of the stimuli when performed on arm, finger, and palm also affects the gap distance, mainly the minimum gap distance for proximal-distal orientation (i.e., along the arm) is bigger than for lateral-medial orientation (i.e., across the arm) [6].

Spatial Patterns across Different Body Parts

Though spatiotemporal patterns let us "draw" a shape, patterns presented to one body part may not be perceived the same as when presented to another part [2].

Previous works show the potential of spatiotemporal vibrotactile patterns; however, the research either investigated only more sensitive body parts (e.g., finger [7], wrist [11], or palm [21, 22, 24]) or have not been proved reliable for an accurate recognition. Those that focused on less sensitive body parts (e.g. abdomen [4]) used relatively larger devices (and thus enlarging the gap distance between actuators, which can increase the distinguishability [6]) with single-activation only. Cholewiak & Craig [2] explored recognition of vibrotactile patterns at finger, palm, and thigh. However, when applying the stimuli to these body parts, neither the patterns nor the devices were identical, thus disallowing the investigation of cross-body vibrotactile pattern recognitions. This investigation explores several spatial dimensions to design spatiotemporal vibrotactile patterns that can be recognized independently on the body parts where users tend to put their smartphone: *arm*, *palm*, *thigh,* and *waist* [10, 20].

MOTIVATION

The spatiotemporal vibrotactile patterns in this paper refer to a number of vibration points located in a 2D grid, a constrained definition that has been used by many previous works [16, 22, 23]. The focus of this paper is not just *distinguishability* (i.e., distinction tasks where users can differentiate stimuli A and stimuli B), we are more interested in patterns that can be *recognized* reliably (i.e., recognition tasks where given a stimuli A, users can recognize it as A instead of other alternatives). As compared to distinguishing, recognition requires a more detailed analysis of stimuli and involves memorization process [2]. Patterns can be distinguished from each other when presented in sequence, yet still incorrectly recognized when presented alone [5].

To better understand human ability to recognize cross-body spatiotemporal vibrotactile patterns, we decided to first focus on recognizability of the most basic patterns, from which more complex patterns are constructed. Arguably, two of the most basic patterns are positional patterns, which consist of a single activation of a vibration motor, and linear patterns, which consist of a sequential activation of two different motors on a line segment. *Positional patterns* are determined by their unique locations on the grid. *Linear patterns* are determined by their starting position, direction, and length.

To understand human ability to recognize these patterns, it must be determined whether a human can reliably recognize: the unique location of a positional pattern as well as the starting position, the direction of a pattern, and the length of a linear pattern. Since cross-body recognition of length has already been investigated [6], we decided to conduct two experiments to investigate these remaining issues:

1) Whether or not humans can reliably recognize the location of a positional pattern within a grid constrained by the dimension of a regular mobile phone across common body parts.

2) Whether or not humans can recognize the direction of a linear pattern within a grid constrained by the dimension of a regular mobile phone across body parts.

PROTOTYPING

We designed a hardware prototype made from acrylic shaped like a smartphone (Figure 2). While mobile phone sizes vary significantly, we focused on a size of phone that could be comfortably placed inside a user's pocket. The dimensions of the prototype are 136 × 70 × 6 mm, which is similar to Samsung Galaxy S5, ranked the 2nd bestselling smartphone worldwide in May 2014[1]. Following previous works [16, 22, 23], we put 9 vibration motors (coin-type Precision Microdrives 310-103) with a diameter of 1 cm on the back of the device in a 3×3 grid configuration (Figure 2).

[1] http://news.yahoo.com/apple-samsung-dominate-list-top-10-best-selling-100853996.html

According to Yatani et al. [22], the distance between two vibration motors should be at least 2 cm. After pretests, we chose a vertical gap distance of 2.5 cm as it can achieve a slightly better accuracy on *arm* and *thigh*. This configuration also ensured that all vibration motors could be in contact with the skin, even for people with small hands. Taking the ratio between proximal-distal and lateral-medial into consideration [6], 2 cm was used for horizontal gap distance.

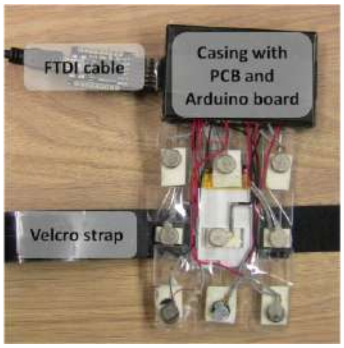

Figure 2: Device platform prototype seen from behind with the 3×3 vibration motors. The black casing contains the Arduino board and PCB. A 3.7V battery is included under the vibration motors.

The vibration motors are powered by a PCB with 9 NPN transistors (BC547). The prototype is controlled using an Arduino Pro Mini microcontroller that receives power and communicates with the PC using a USB cable.

EXPERIMENTS

A total of four experiments were conducted. The first two experiments investigated human ability to recognize basic spatiotemporal vibrotactile patterns. The next two experiments aimed to validate the effectiveness of a set of cross-body patterns we created based on the findings of the first two experiments. The four experiments shared significant commonality in apparatus, procedure, and task, thus we describe these shared components below:

Common Apparatus

The experiment was performed with the vibration grid prototype (described in the previous section) connected to a Windows 7 desktop with a 2.83 GHz Intel Core 2 Quad with 4 GB of RAM. The experimental software was developed in-house using Java 7. The software was used to run the experiment as well as to communicate the patterns to be generated to the prototype. The experimental interface offered a canvas so that our participants could draw the patterns as they perceived them. During the test blocks, the software displayed the representation of the patterns as drawn by the participants using a grid layout template.

Common Procedure

To avoid possible disturbance of sound caused by the vibration motor, we asked participants to wear a headset playing pink noise for the first three experiments [17]. The last experiment involved a primary task with audio feedback, thus pink noise mask was not used. All patterns were tested on all four common body parts [20] (*palm*, *arm*, *thigh,* and *waist*) for the first three experiments; for the last study, participants chose two body parts where their phone was typically placed. During the experiment, participants tied the prototype onto each of the body parts using Velcro straps. For each body part, there were two possible sides (dominant or non-dominant) where the prototype could be placed. According to a participant survey, participants preferred to place the phone on the non-dominant side for *palm* and *arm* to intentionally leave the dominant hand/arm for primary tasks. Conversely, the dominant side was typically preferred for *thigh* and *waist* for easier retrieval and replacement of the phone.

Common Task and Stimuli

In all experiments, participants were asked to recognize a set of spatiotemporal vibrotactile patterns. Although the sequence of play and spatial arrangement of vibrotactile patterns differ, each vibration was activated for exactly 600 ms followed by a 200 ms gap (if any) as suggested by Saket et al. [17]. To allow smooth transition between the vibration and the gap, each vibration started with a fade-in effect and ended with a fade-out effect as suggested in *SemFeel* [24].

EXPERIMENT 1: RECOGNIZE POSITIONAL PATTERNS

As previously mentioned, Experiment 1 focused on whether participants could reliably recognize the location of a positional pattern within a grid across common body parts.

Participants

Eight participants (3 females, 7 right handed) from 18 to 38 years old (M = 24.4, SD = 6.8) were recruited from within the university community.

Tasks and Stimuli

In the 3x3 grid, there were 9 possible positions, which could be divided into three categories: on-axis, off-axis, and center (see Figure 3). Since each on-axis or off-axis position is symmetric to another position within the same category, we only chose 2 positions each from the on-axis and off-axis categories plus the center position as the test set (5 positions total).

Procedure

We want to emphasize the difference between the actual position where the vibration happens on the grid vs. the perceived position a participant can feel it. For example, a participant may feel that a vibration comes from the top left corner; however, it is actually played on the middle left position. In this case, the actual position (middle left) is different from the perceived position (top left). However, such a difference does not affect the recognizability of a positional pattern as long as it is consistently perceived.

To familiarize participants with the patterns and to understand their perceived positions, we designed the following training phase: participants were asked to play all 5 patterns in the same order at their own pace 3 times. They were asked to record the perceived position of each pattern on a furnished sheet of paper with preprinted grids. After these three playbacks, they would input a drawing reflecting their own perception of the pattern.

To further familiarize participants with the patterns, they were then asked to recognize the 5 patterns played in a random order from the perceived positions they had recorded earlier. Feedback was provided on whether or not their selections were correct. A participant could choose either to play the pattern again or proceed to the next trial. After the training phase, participants proceeded to the actual experiment in which no feedback was provided.

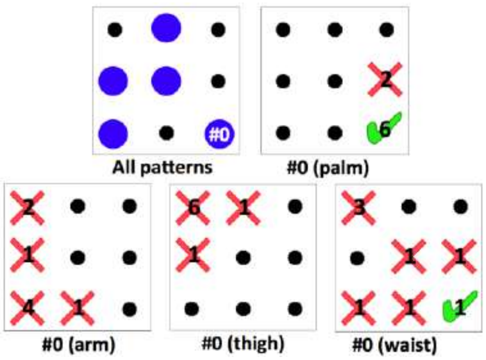

Figure 3: Top-left: patterns used in Experiment 1. Each blue circle corresponds to a pattern with the indicated position. Other panels show how participants perceived the pattern #0 on each body part. Numbers in black indicate how many participants perceived the vibration at the specified location.

Design

A within-subject design was used with only one independent variable with four levels: *body part {arm, palm, thigh, waist}*. This variable was counterbalanced using Latin Square. We measured recognition rate as the only dependent variable. Participants could take voluntary breaks between blocks. Each participant performed the entire experiment at one sitting, including breaks, in around 40 minutes. The design included the following: 8 participants × 4 body parts × [4 (training blocks) × 5 (stimuli) + 4 (test blocks) × 5 (stimuli)] = 1280 trials.

Results

Accuracy

The overall accuracy was low (50.6%), which suggests participants had difficulty in recognizing the absolute location of a positional pattern. There were significant differences between body parts: an ANOVA showed a significant effect of *body part* on the accuracy ($F_{3,21}$=1.19, p<.001). The most precise location was the *palm* (78.9%), followed by the *thigh* (46.7%), the *waist* (42.2%), and the *arm* (34.5%). Pairwise *t*-tests with Bonferroni corrections showed significant differences between *palm* and all three other body parts (all p<.01).

Perceived Position for Different Body parts

A total of 40 drawings were generated for each body part (8 participants x 5 patterns). The analysis of participants' drawings revealed that the only body part where the perceived positions generally matched the actual positions was the *palm* (27/40). On *arm*, almost all perceived locations were different from the actual position. However, most of the errors (17/40) were due to a mirrored perception towards the vertical axis. Using pattern #0 as an example, as shown in Figure 3, none of the participants perceived the pattern from the correct source location on *arm*. Half (4/8) perceived it as the mirrored position across the vertical axis; other participants mistook it for its diagonal counterpart (2/8) or neighboring points around the mirrored position (2/8). On *thigh*, perception seemed to be inverted to both vertical and horizontal axes (17/40). This can especially be seen on pattern #0 (Figure 3) where 6/8 participants incorrectly perceived the pattern as coming from the diagonal counterpart location (combination of both horizontal and vertical mirroring). Finally, on *waist*, results would also suggest errors from symmetry on both axes (18/40), or vertical axis alone (6/40). Other errors were due to participants not localizing precisely the absolute position of the stimuli.

Discussion

The result of this study shows that the accuracy observed on *palm* is comparable, but slightly lower, to *SemFeel* [24] or *T-Mobile* [21]. Participants were unable to precisely locate the actual position on other body parts. The lower accuracy on these parts comes from a perception problem, as shown by the drawings of participants: on other parts than *palm*, drawings became widespread. This suggests that participants were *roughly* able to locate the vibration in a particular area, (i.e., that the perceived location was in the same area of the grid as the actual location). Accuracy could also be increased by increasing the distance between each vibration motor but would require a larger prototype.

Another important result was the symmetries we observed from the drawings. Previous studies have shown that perception varies according to posture [12, 19]. In our experiment, participants were seated and were thus looking at their *thigh* and *waist* from above as if they were reading a book put on these body parts, explaining the horizontal axis inversion. The inversion towards vertical axis can be explained by the fact that on *thigh* and *waist,* participants would consider that the *top* of the phone was the part appearing on the top part of their field of vision, instead of the part that was on the higher position on their body. The same inversion happened on *arm* because participants were picturing the phone as vertically flipped compared to the *palm*. On *waist*, many participants had symmetry on both axes, but 2 of them seemed to have only vertical axis symmetry. This varying spatial orientation on *waist* was already suggested by Vo et al. [19]. Perceived orientations for each body part are summarized in Figure 1b. Since fixed orientation of the phone cannot be enforced in real life scenarios; therefore, a consistent perception of orientation on any body part cannot be guaranteed.

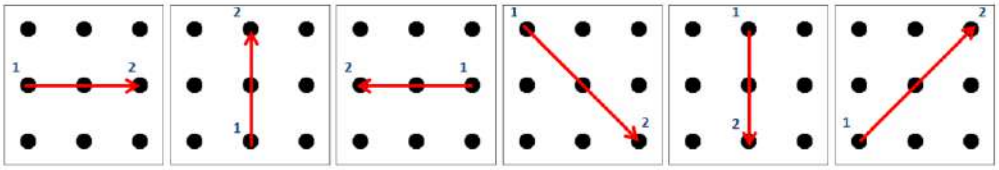

Figure 4: Patterns used in Experiment 2. The blue numbers indicate the order of the sequence of vibration motors.

To design cross-body patterns, the imprecise absolute localization, the symmetry problems, and the fact that orientation of the phone cannot be enforced should be taken into account: translated or rotated variations of patterns should be avoided. For example, patterns drawing letters such as {p, q, b, d} could easily be confused. The only body part with a stable representation and orientation is the *palm*.

EXPERIMENT 2: RECOGNIZE LINEAR DIRECTIONS

In Experiment 2, we further investigated users' perception of the orientation of linear patterns across body parts.

Participants, Task, and Stimuli

Twelve participants (3 women, 8 right handed) from 20 to 27 years of age (M = 23.3, SD = 2.1) were recruited from within the university community. None had participated in the previous experiment. Six linear patterns, shown in Figure 4, were selected for experimentation.

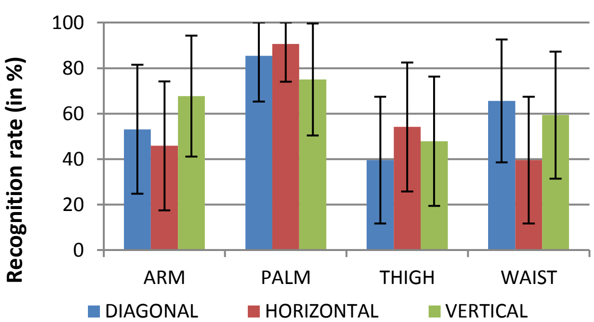

Figure 5: Recognition rate for each body part depending on the stimuli. Error bars are .95 confidence intervals.

Procedure and Design

The procedure was performed exactly the same as Experiment 1 but with 6 patterns instead of 5. Participants were not informed that the patterns were all linear but were told that a sequence of two vibrations would be played, which could come either from the same or different vibration motors. A 4×3 within-subject design was used with two independent variables: *body part {palm, arm, thigh, waist}* and *orientation {vertical, horizontal, diagonal}*. *Body part* was counterbalanced using Latin Square, and *orientation* was randomized within blocks. The dependent measure was the pattern recognition rate. The experiment lasted for 50 minutes. The design of the experiment was 12 participants × 4 body parts × [4 (training) × 6 (stimuli) + 4 (test) × 6 (stimuli)] = 2304 trials.

Results

Accuracy

The overall recognition rate in Experiment 2 was 60.3% with significant variations across body parts (Figure 5). A repeated-measures ANOVA showed a significant effect of *body part* ($F_{3,33}$=9.71; p<.0001). Pairwise comparisons suggest that *palm* (83.7%) was the most accurate, performing significantly better than all other parts: *arm* (55.5%), *thigh* (47.2%) and *waist* (54.9%) (all p<.0001).

Orientation did not have a significant effect on the recognition rate (p=.69), even though vertical orientation (62.5%) was slightly better when compared to horizontal (57.5%) and diagonal (60.9%). We observed an interaction between *body part* and *orientation* ($F_{6,66}$=3.07; p=.01), explainable by the fact that on *waist*, there were significant differences between both vertical (59.4%) and diagonal orientation (65.6%) and horizontal (39.6%) (all p<.01). The *waist* has a more homogeneous structure on the lateral-medial axis, while the proximal-distal axis of the belly involves ribs and fleshy parts.

	Diagonal	Horizontal	Vertical	Other
PALM				
Diagonal	**54.1%**	4.1%	8.3%	33.3%
Horizontal	16.6%	**70.8%**	0%	12.5%
Vertical	16.6%	12.5%	**58.3%**	12.5%
ARM				
Diagonal	**41.6%**	4.1%	16.6%	37.5%
Horizontal	25%	**54.1%**	4.1%	16.6%
Vertical	33.3%	0%	**37.5%**	29.1%
WAIST				
Diagonal	**37.5%**	8.3%	37.5%	16.6%
Horizontal	37.5%	**29.1%**	12.5%	20.8%
Vertical	25%	8.3%	**54.1%**	12.5%
THIGH				
Diagonal	**25%**	16.6%	25%	33.3%
Horizontal	20.8%	**41.6%**	12.5%	25%
Vertical	25%	4.1%	**41.6%**	29.1%

Table 1: Confusion matrix for stimulus (row) and reported (column) pattern per body part. Non-strictly diagonal patterns were classified as "Other" (e.g. a line between (0,0) and (1,2)).

Perception and Drawings

To analyze the difference between perceived vs. actual orientation, we produced a confusion matrix shown in Table 1. Unsurprisingly, *palm* is where the perception was the most accurate, with 61.1% of drawings correct. The main result from these drawings is that users' perception of the patterns is not clear enough.

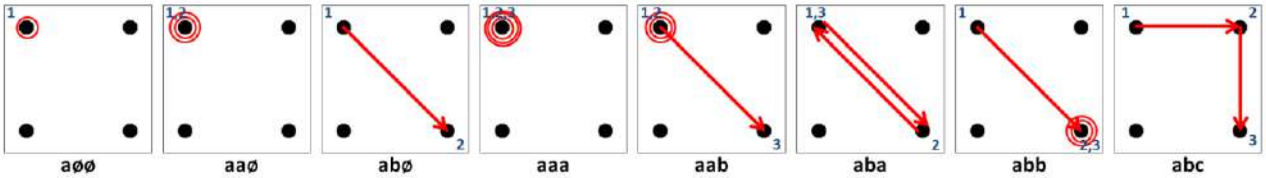

Figure 6: OmniVib patterns used in Experiment 3 and 4, labeled according to our naming convention.

Discussion

Similar to actual position, actual orientation was again difficult to perceive correctly across body parts (see Table 1). This may due to the fact that on *arm*, *thigh,* and *waist*, the device might be slightly tilted, making it hard to perceive an accurate vertical axis. Patterns are thus either recognized as *diagonal* or *"other"* (Table 1 caption).

Despite the fact that neither orientation nor position can be accurately recognized, we discovered one feature that can be distinguished reliably for almost all participants across body parts based on our analysis of their drawings. Out of the 288 drawings produced (12 participants × 4 body parts × 6 patterns), only one indicated that the two vibrations were perceived as coming from the same place, which indicates that participants can accurately distinguish whether or not the two subsequent vibrations come from the same location.

This finding inspired us to design a set of cross-body spatiotemporal vibrotactile patterns.

OMNIVIB: DESIGN OF CROSS-BODY PATTERNS

Based on our previous results, we designed OmniVib, a set of patterns (Figure 6) recognizable on the four body parts.

Dimensions and Constraints

This set of patterns was defined under these considerations:

1) The number of activations of vibration motors involved in the pattern (1, 2 or 3).
2) Whether a sequential play of two motors come from the same location or not.
3) The absolute location of a particular vibration does not matter. Thus, a linear pattern going from left to right is considered to be the same as a pattern right to left, since it involves two sequential vibrations happening on different vibration motors.
4) Finally, we decided to reduce the number of vibration motors used (9 in a 3×3 grid) and only considered the most distant ones (four vibration motors in the corners), reducing the grid to a dimension of 2×2.

Based on these considerations, we decided to design patterns consisting of one, two, or three sequential vibrations. This allowed us to create a set of 8 patterns.

Pattern Generation

We define N vibration motors and T number of intervals within a pattern. If we use $N = 3$, $T = 3$ as an example, N is represented by $N+1$ unique letters: *a, b, c*, and *ø*, where *a*, *b*, and *c* represent the activation of a particular vibration motor and *ø* represents the absence of an activation; T represents the maximum number of vibrations that will be played in a pattern. With this, we can mathematically derive all the possible combinations.

Among these combinations, many cannot be reliably distinguished by users as indicated by our experimental results. For example, users cannot distinguish (*a, *,* *) from (*b, *,* *) from (*c, *,* *) if these patterns are played at separate times across different body parts (note *,* represents any unique combination of 2 subsequent plays of vibration motors). Similarly *(a, b,* *) is equivalent to (*a, c,* *) and (*b, c,* *), etc. Also, since we do not consider temporal variations, our design does not consider (*a, ø, b*) as valid. By removing all the equivalent patterns, we end up with 8 unique designs (Figure 6) as follows: (*a*, *ø*, *ø*), (*a*, *a*, *ø*), (*a*, *a*, *a*), (a, a, b), (*a, b, ø*), (*a, b, a*), (*a, b, b*), (*a, b, c*).

EXPERIMENT 3: CROSS-BODY PATTERNS

To validate the effectiveness of our design, we conducted a third experiment.

Participants, Task, and Stimuli

Twelve participants (5 women, 10 right handed) ranging from 18 to27 years of age (M = 21.3, SD = 2.8), recruited from within the university community, volunteered. None of them had participated in any previous experiment. The 8 patterns shown in Figure 6 were used for the study.

Procedure and Design

The procedure was the same as those in the previous studies but with 8 stimuli. Because we only used four vibration motors (in a 2×2 setup), the canvas in the drawing phase was updated to reflect this change. A 4×8 within-subject design was used with two independent variables: *body part {palm, arm, thigh, waist}* and *pattern*. *Body part* was counterbalanced using Latin Square, and *pattern* was randomized within blocks. The dependent measure was the pattern recognition rate. Participants could take voluntary breaks between blocks. Each participant performed the entire experiment at one sitting, including breaks, in approximately 1 hour. In summary, the design of the experiment was 12 participants × 4 body parts × [4 (training blocks) × 8 (stimuli) + 4 (test blocks) × 8 (stimulus)] = 3072 trials.

Results

Accuracy across body parts

We observed a significant improvement of cross-body recognition (M=86.3% across body parts, Figure 7). A repeated-measures ANOVA yielded a significant effect of *body part* on accuracy ($F_{3,33}$=5.15, p<.01). Pairwise comparisons showed significant differences (all p<.01) between all paired combinations except between *arm* (92.7%) and *palm* (91.1%), and *waist* (81.2%) and *thigh* (80%) (both p>.05).

Accuracy across patterns

Our results suggest large differences between patterns. The ANOVA confirmed the impact of *pattern* factor on the results ($F_{7,77}$=6.41 ; p<.01, Figure 8). Pairwise *t*-tests with Bonferroni corrections showed significant differences between pattern *aøø* and all other patterns (all p<.05), as well as between pattern *abc* and all other patterns but *aab* (all p<.05). No interactions between *body part* and *pattern* were observed (p=.74).

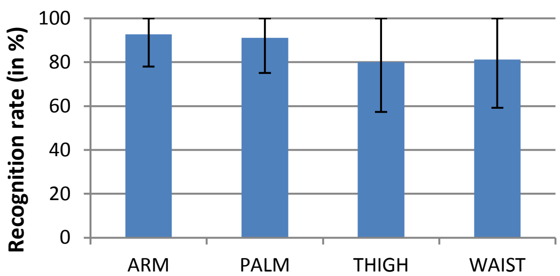

Figure 7: Recognition rates for each body part. Error bars are .95 confidence intervals.

Learning effect

We were also curious to discover if our participants would improve recognition over time and compared results between *blocks*. An ANOVA showed no significant differences (p=.45) of accuracy among *blocks*, which suggests good recognition of these patterns can be achieved with minimum training.

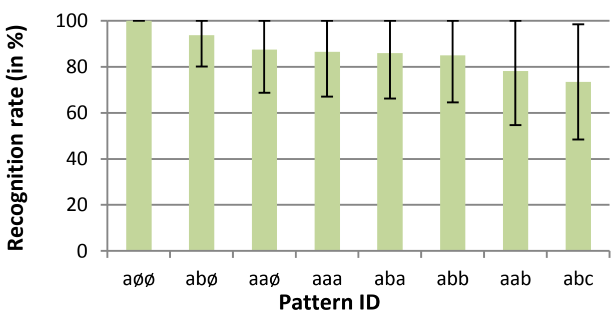

Figure 8: Recognition rate for each pattern in decreasing order. Error bars are .95 confidence intervals.

Perception and Drawings

We analyzed the drawings of the participants. A drawing was considered as correct as long as the participants felt the correct amount of vibrations and that the participants perceived the change of locations within patterns. Participants were able to accurately perceive and draw an average of 96.25% accuracy on *arm*, 97.5 on *palm*, 88.75% on *waist* and 86.25% on *thigh*.

Discussion

The results of the experiment are particularly encouraging for designing cross-body spatiotemporal vibrotactile patterns.

By comparing the recognition rate of each pattern, it's not surprising to see that the simplest pattern (*aøø*) achieved 100% recognition rate while the most complex pattern (*abc)* received the lower recognition rate. This indicates that if only 7 patterns are needed, *abc* can be discarded. Without it, the cross-body accuracy can be increased to 88.1%.

EXPERIMENT 4: EXTERNAL VALIDITY

The vocabulary of patterns that we designed was proven to be recognizable by our participants on four different body parts in a controlled experiment but was not tested with real world scenarios. To confirm the external validity of our results, we designed a fourth experiment.

Participants

Six participants (4 women, all right handed) ranging from 19 to 24 years of age (M = 21, SD = 1.7), recruited from the university, volunteered for the experiment.

Task and stimuli

Primary Task. During the experiment, participants watched a movie of their choice, which increased the likelihood they would engage in the primary task.

Secondary Task. We tested the participants on a scenario where they were expecting an important e-mail. Participants had to choose between 5 patterns they preferred in our set of 8 and map them to 5 mobile applications: *instant messages*, *e-mails*, *social media*, *calendar*, and *low battery* (which are identified as the most commonly used mobile notification by Shirazi et al. [18]).

Stimuli. During Experiment 4, participants received random notifications from all the 5 scenarios. After receiving a notification, participants had to answer a prompt asking them to choose from a list which scenario corresponded to the notification they received.

Design

A within-subject design was used with one independent variable: *body part*. Participants wore the prototype on their *palm* and could choose the other site from the three alternative body parts (*arm*, *thigh*, *waist*). All participants (6/6) chose *thigh*, the location with the lowest recognition rate and also a body part with inverted perception on both axis (compared to palm), which makes it a difficult yet interesting comparison with *palm*. We measured the success rate of trials. The *body part* factor was counter balanced between participants and patterns were randomized within blocks. Experiment 4 lasted 25 minutes. The design of the experiment was 6 participants × 2 body parts × [5 (stimuli) × 2 (repetitions)] = 120 trials.

Procedure

At the beginning of the experiment, participants were presented with all 8 patterns we created. The training was performed on their palm only. After 3 minutes, we asked them to choose 5 patterns and map them to the 5 scenarios mentioned above. We asked them to create the mapping to simulate real life scenarios: when receiving a notification, participants not only had to recognize the pattern played but also had to link it to the corresponding scenario it maps. The testing was carried out under two conditions: one for *palm* and one for *thigh*. Each condition was tested for 10 minutes.

Results

Our 6 participants achieved a success rate of 87.5% (90% on *palm* and 85% on *thigh*). While we hypothesized that the participants would choose the simple patterns (*aaø*, *aøø*, *abø*), each available pattern was chosen by at least 2 participants (see Table 2). Participants related that they tried to choose patterns as distinct and different as possible, which explained why they chose patterns with 3 vibrations (*aaa* and *aba*).

Pattern ID	aaø	abb	abc	aaa	aba	aøø	aab	abø
Number of selections	5	2	2	4	5	6	2	4

Table 2: Frequency of choice for each pattern.

An interesting observation is that 5/6 participants seemed to use the number of vibrations as an indicator for urgency; although one participant regarded 1 vibration as the most urgent, the others regarded 3 vibrations as the most urgent.

Considering that participants only trained on *palm*, this study shows that they were still able to recognize the patterns on different body parts, suggesting that the patterns can be recognized across multiple body parts.

OVERALL DISCUSSION

Spatial Dimensions

Our results suggest that actual position of a vibration motor and actual orientation cannot be reliably recognized within the size of a regular mobile phone. Thus, in a given set of patterns, the designer should avoid patterns that are translated variations of other patterns, unless the patterns are designed to be used on the palm only. This limits the possibility of drawing meaningful patterns overall.

Mental Representation of Spatial Orientation

Depending on where the stimulus was applied, participants perceived the stimuli differently determined by their mental representations of the spatial orientation. On *arm*, participants tended to have the same mirrored representation on a vertical axis. On thigh was also consistent with inversion on both axes. On waist, as also shown by Vo et al. [19], the mental representation is not always consistent and can also vary over time. This mental representation problem also suggests that designers should be careful about symmetry problems and thus not use a pattern that is a rotated/mirrored version of another one. This representation problem can explain why the circular patterns investigated in *SemFeel* [24] have high error rates.

Extensibility

The vocabulary we generated can be extended by changing the value of either N or T or both. For example, by changing N to 2 and T to 4, there are a total of 15 unique patterns as follows (*a, ø, ø, ø*), (*a, a, ø, ø*), (*a, a, a, ø*), (*a, a, a, a*), (*a, a, b, ø*), (*a, a, a, b*), (*a, a, b, a*), (*a, a, b, b*), (*a, b, ø, ø*), (*a, b, a, ø*), (*a, b, b, ø*), (*a, b, a, a*), (*a, b, a, b*), (*a, b, b, a*), (*a, b, b, b*). This could potentially increase the total number of recognizable patterns.

Real Life Applicability

In Experiment 4, we investigated how users would perceive a reduced set of vibrotactile spatiotemporal patterns while engaged in a primary task. We believe that OmniVib are ready be implemented on today's smartphones with extra vibration motors. One potential issue is that the device might not always be in close contact with the skin, whereas in our experiments, we made sure the device was firmly tied on the user. This issue can be alleviated by using better quality and stronger vibration motors, as well as slightly curved phones. Another improvement is adding panels on the back of the phone around each vibration motor to isolate the vibration and make it easier to distinguish, as suggested by *T-Mobile* [21].

LIMITATIONS

Although our results were promising, they are tested on short-term recognition and with a limited number of participants. To further validate the results, a longitudinal study with more participants could be performed. Additionally, the results obtained from our experiments were based on the size of a regular phone; findings in Experiment 1 and 2 may differ depending on phone size.

The vibration motors used in the experiment were off-the-shelf vibration motors. Using better quality vibration motors could also positively impact the results. Another limitation comes from physiological factors: during our pretests, we found out that slightly overweight participants tended to be less sensitive to vibration and thus had trouble recognizing patterns, especially on the waist. Also, some volunteers were too skinny to wear the prototype on their arm and could not take part in the experiment.

CONCLUSION AND FUTURE WORK

In this paper, we proposed OmniVib, a set of spatiotemporal vibrotactile patterns that can be recognized (>80%) on *arm, palm, thigh and waist.* OmniVib relies on two dimensions: whether two sequential vibrations are from the same position or not and the number of vibrations involved in the pattern. This set of patterns was designed according to the results of two preliminary studies that showed that participants cannot accurately recognize positional and linear patterns on body parts other than *palm*. These experiments also highlighted symmetry-related problems on perception of vibrations. We also validated OmniVib in a more realistic setting.

In future studies, we would like to extend the size of our set of patterns by increasing the length (*T* dimension) of our vocabulary. We also have interest in testing a prototype with a concave-shaped back so that the vibration motors could felt more easily on *arm* and *thigh*.

ACKNOWLEDGMENTS

This work is part of the NUS-Chalmers collaboration and is funded by Swedish Foundation for International Cooperation in Research and Higher Education (STINT, grant 2013-019). We would like to thank the members of NUS-HCI Lab and INRIA's InSitu Lab for their thoughtful comments; as well as Mounia Ziat and Denys J.C. Matthies for their help and recommendations.

REFERENCES

1. Brewster, S., Brown, L.M. Tactoncs: Structured Tactile Messages for Non-Visual Information Display. In *5th Australian User Interface Conference (AUIC) 2004*. Australian Computer Society, Inc. (2004), 15-23.
2. Cholewiak, R. W. Vibrotactile pattern recognition and discrimination at several body sites. In *Perception & Psychophysics*, vol. 35-6 (1984), 503-514.
3. Cholewiak, R. W., Collins, A. A. Vibrotactile localization on the arm: Effect of place, space, and age. *Perception & Psychophysics*, 65-7 (2003), 1058-1077.
4. Cholewiak, R. W., Collins, A. A. Vibrotactile localization on the abdomen: Effect of place and space. In *Perception & Psychophysics*, 66-6 (2004), 970-987.
5. Craig, J. C., Sherrick, C. E. Dynamic Vibrotactile Displays. In *Tactual Perception: A Sourcebook*. Cambridge University Press (1982), 209-233.
6. Gibson, G.O., Craig, J. C. Tactile spatial sensitivity and anisotropy. In *Perception & Psychophysics*, vol. 67-6 (2005), 1061-1079.
7. Hoggan, E. Anwar, S., Brewster, S. Mobile multi-actuator tactile displays. In Proc. HAID 2007, Springer-Verlag, Berlin (2007), 22-33.
8. Horner, D. T., Craig, J. C. A comparison of discrimination and identification of vibrotactile patterns. In *Perception & Psychophysics*, 45-1 (1989), 21-30.
9. Huisman, G., Frederiks, A. D., Van Dijk, B., Hevlen, D., Krose, B. The TaSST: Tactile sleeve for social touch. In *World Haptics Conference (WHC)*. 21-216.
10. Karuei, I., MacLean, K.E., Foley-Fisher, Z., MacKenzie, R., Koch, S., El-Zohairy, M. Detecting vibrations across the body in mobile contexts. In *Proc. CHI'11*. ACM (2011), 3267-3276.
11. Lee, S.C., Starner, T. BuzzWear: alert perception in wearable tactile displays on the wrist. In *Proc. CHI 2010*. ACM (2010), 433-442.
12. Parsons, L.M., Shimojo, S. Perceived spatial organization of cutaneous patterns on surfaces of the human body in various positions. In *Journal of experimental psychology: Human perception and performance 13*, 3 (1987), 488-504.
13. Park, Y., Lim, C., Nam, T. CheekTouch: an affective interaction technique while speaking on the mobile phone. In *CHI EA '10*. ACM (2010), 3241-3246.
14. Pasquero, J., Stobbe, S. J., Stonehouse, N. A haptic wristwatch for eyes-free interactions. In *Proc. CHI 2011*. ACM (2011), 3257-3266.
15. Rantala, J., Myllymaa, K., Raisamo, R., Lylykangas, J., Surakka, V., Shull, P., and Cutkosky, M. (2011). Presenting Spatial Tactile Messages with a Hand-Held Device. In *Proc. World Haptics 2011*, IEEE, pp. 101-106.
16. Sahami, A., Holleis, P., Schmidt, A., Häkkilä, J. Rich tactile output on mobile devices. In *Proc. Ambient Intelligence 2008*. Springer (2008), 919-928.
17. Saket, B., Prasojo, C., Huang, Y., Zhao, S. Designing an effective vibration-based notification interface for mobile phones. In *Proc. CSCW'13*. ACM, 1499-1504.
18. Shirazi, A. S., Henze, N., Dingler, T., Pielot, M., Weber, D., Schmidt. Large-Scale Assessment of Mobile Notifications. In *Proc. CHI'14*. ACM, 3055-3064.
19. Vo, D.-B., Lecolinet, E., and Guiard, Y. Belly Gestures: Body Centric Gestures on the Abdomen. *In Proc. NordiCHI'14*. ACM (2014), 1-10.
20. Wiese, J., Saponas, S., Brush, A.J.B. Phoneprioception: enabling mobile phones to infer where they are kept. In *Proc. CHI 2013*. ACM (2013), 2157-2166.
21. Yang, G., Jin, Y., Jin, M., Kang, S. T-Mobile: Vibrotactile Display Pad with Spatial and Directional Information for Hand-held Device. In *International Conference on Intelligent Robots and Systems* (2010).
22. Yatani, K., Banovic, N., Truong, K. SpaceSense: representing geographical information to visually impaired people using spatial tactile feedback. In *Proc. CHI 2012*. ACM (2012), 415-424.
23. Yatani, K., Gergle, D., Truong, K.N. Investigating Effects of Visual and Tactile Feedback on Spatial Coordination in Collaborative Handheld Systems. In *Proc. CSCW 2012*. ACM (2012), 661-670.
24. Yatani, K., Truong, K.N. SemFeel: a user interface with semantic tactile feedback for mobile touch-screen devices. In *Proc. UIST 2009*. ACM (2009), 111-120.